CHANDRA DEEP X-RAY OBSERVATION ON THE GALACTIC PLANE

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Abstract

Using the Chandra ACIS-I instruments, we have carried out the deepest X-ray observation on a typical Galactic plane region at $l \approx 28.^\circ 5$, where no discrete X-ray sources have been known previously. We have detected, as well as strong diffuse emission, 275 new point X-ray sources (4 σ confidence) within two partially overlapping fields ($\sim$250 arcmin^2 in total) down to $\sim 3\times10^{-15}$ erg s^{-1} cm^{-2} (2 – 10 keV) or $\sim 7 \times 10^{-16}$ erg s^{-1} cm^{-2} (0.5 – 2 keV). We have studied spectral distribution of these point sources, and found that very soft sources detected only below $\sim$ 3 keV are more numerous than hard sources detected only above $\sim$ 3 keV. Only small number of sources are detected both in the soft and hard bands. Surface density of the hard sources is almost consistent with that at high Galactic regions, thus most of the hard sources are considered to be Active Galactic Nuclei seen through the milky way. On the other hand, some of the bright hard X-ray sources which show extremely flat spectra and iron line or edge features are considered to be Galactic, presumably quiescent dwarf novae. The soft sources show thermal spectra and small interstellar hydrogen column densities, and some of them exhibit X-ray flares. Therefore, most of the soft sources are probably X-ray active nearby late type stars.

Key words: Missions: Chandra – Galaxy: milky way – X-rays: Star

1. Introduction

The Galactic plane has been known to be a strong hard X-ray (2 – 10keV) emitter for nearly 20 years (e.g., Worrall et al. 1982; Warwick et al. 1985; Koyama et al. 1986). The emission forms a narrow continuous ridge, thus it is often called the Galactic Ridge X-ray Emission (GRXE). GRXE exhibits emission lines from highly ionized heavy elements such as Si, S and Fe, which suggests that GRXE is originated from thin hot plasmas with a temperature of several keV (Koyama et al. 1986). However, whether GRXE is composed of numerous point sources or truly diffuse emission has been an unsolved problem, mostly because previous instruments have not had good enough spatial resolution in hard X-ray band (> 2 keV). The Chandra X-ray mirror has a superior angular resolution ($\sim 0.5''$), which allows one to distinguish numerous dim point sources and truly diffuse X-ray emission. Therefore, we planned Chandra observation on a typical Galactic plane region to resolve origin of the hard X-ray emission from the Galactic plane.

2. Observation

Using Chandra ACIS-I, we observed a region around $(l, b) \approx (+28^\circ.45, -0^\circ.2)$, where the ASCA satellite could not find any point sources brighter than $\sim 2 \times 10^{-13}$ erg s^{-1} cm^{-2} (2 – 10 keV) (Yamauchi et al. 1996; Kaneda et al. 1997). We carried out two pointings, each for 100 ksec in AO1 and AO2, with slightly overlapping the fields (Figure 1). Total area of the observed field is $\sim$ 250 arcmin^2. The first result from the AO1 result was published in Ebisawa et al. (2001).

3. Data Analysis and Results

3.1. Point Source Search

In our fields, we see many point sources as well as strong diffuse emission. We have carried out point source search using the "wavdetect" program in the CIAO data analysis package. We have searched for sources in the 0.5 – 3 keV, 3 – 8 keV and 0.5 – 8 keV independently. The sources which exceed 4 σ significance either in the three energy bands are considered as the true detection. On the AO1 and AO2 overlapping field, we searched for sources for AO1 and AO2 separately, and added the two significances quadratically.

Thus, we have detected 275 new X-ray point sources within the AO1 and AO2 field of view. In the soft band, 183 sources have been detected, while in the hard band we have detected 79 sources. Note that only 26 sources have been detected both in the soft and hard bands. Our sensitivity is $\sim 3 \times 10^{-15}$ erg s^{-1} cm^{-2} (2 – 10 keV) and $\sim 7 \times 10^{-16}$ erg s^{-1} cm^{-2} (0.5 – 2 keV).

Four soft sources at $(\alpha, \delta) = (280.^\circ 99, -3.^\circ 91)$ actually seem to compose an extended feature, that is probably a blob in the super nova remnant AX J 1843.8–0352/G28.6–0.1 (Koyama et al. 2002). We tried to identify other new X-ray point sources with those in published catalogs. About

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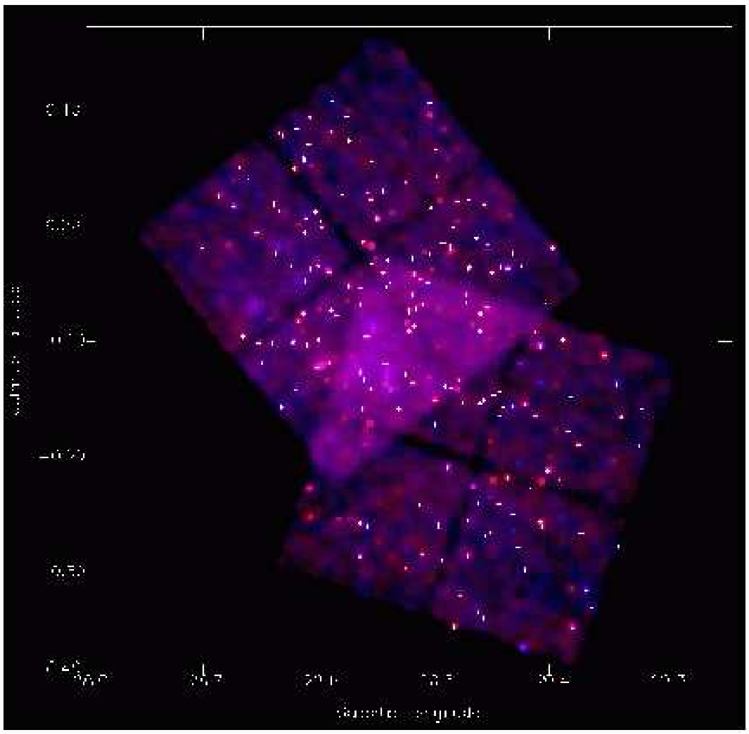

Figure 1. Superposed image of the two Chandra observations (exposure is not corrected). South is AO1 and North is the AO2 fields, each for 100 ksec exposure. Hard X-rays in 3 – 8 keV are expressed in blue, and soft X-rays in 0.5 – 3 keV are shown in red. The 275 detected point sources are shown in crosses.

a dozen of the soft sources have been identified in the United States Naval Observatory A2.0 catalog with the R magnitude brighter than ~ 18. On the other hand, no hard sources have been optically identified. Deep optical or near infrared follow-up observations are anticipated to identify some of these hard X-ray sources[1].

[1] We have been granted two nights to observe this field in the near-infrared band with the ESO/NTT SOFI.

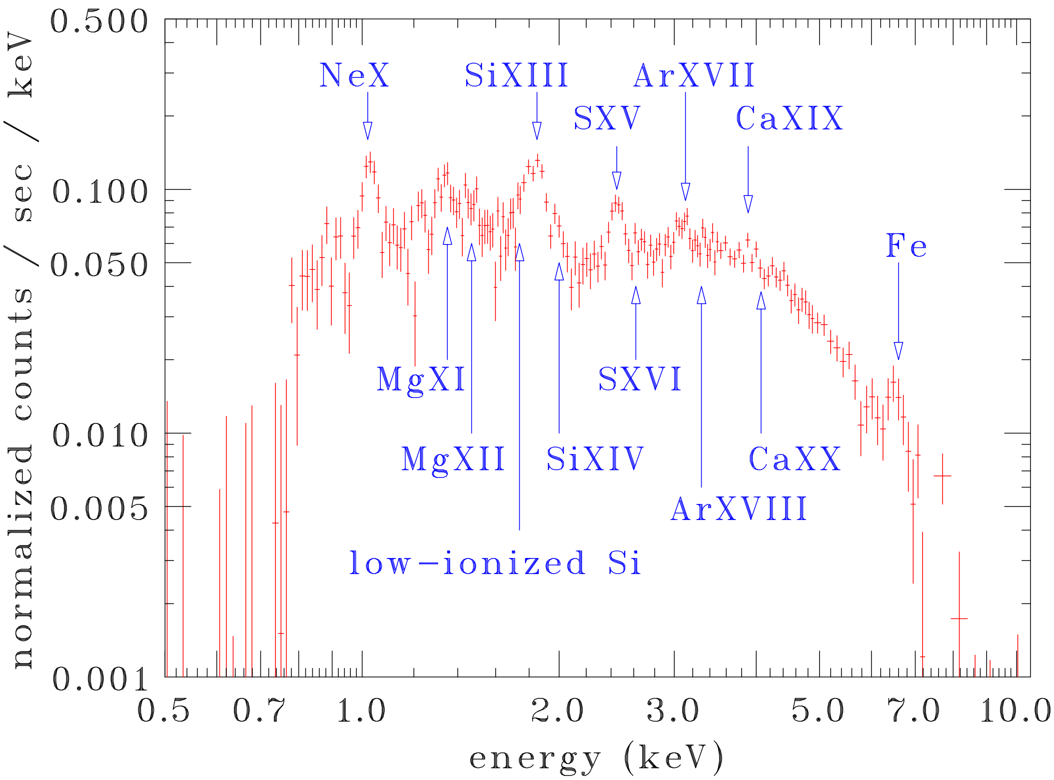

Figure 2. Energy spectra of the total X-rays in our fields.

3.2. Origin of the Galactic Hard X-ray Emission

After subtracting the expected non X-ray background, we calculated the total hard X-ray energy flux from our field of view, that was $\sim 1.1 \times 10^{-10}$erg s^{-1} cm^{-2} ($2-10$ keV). On the other hand, total hard X-ray flux calculated by combining all the point sources was $\sim 10^{-11}$erg s^{-1} cm^{2} ($2-10$ keV); namely point sources account for only $\sim 10\%$ of the total hard X-ray flux in the field of view. We compared surface density of the hard point sources in our field view with those at high Galactic blank fields (e.g. Giacconi 2001). After the Galactic absorption ($\sim 6 \times 10^{21}$ cm^{-2}) is taken into account, we found the number density of the hard X-ray sources in our Galactic plane field is comparable to those in high Galactic bland fields (Ebisawa et al. 2001). Therefore, we concluded that most of the point sources are extragalactic, presumably active galaxies seen through the Galactic disk. Present result clearly indicates that GRXE is diffuse origin, which indicates omnipresence of the energetic plasma along the Galactic plane.

3.3. Diffuse Emission Energy Spectra

We have made energy spectra of the Galactic X-rays (diffuse emission and Galactic point sources) by subtracting the non X-ray background and contribution of the extragalactic component. Before subtracting the background, we performed the CTI correction on our event lists in order to improve the energy resolution. We took the extragalactic observations on HDF-N (sequence # 90030 and 900061), whose exposure time is 337 ksec in total. We subtracted the energy spectrum of the HDF-N from that of our fields, by adjusting the normalization of the former so that the instrumental Ni K_α lines in the two energy spectra cancel each other. The resultant energy spectrum is shown in Figure 2. Numerous emission lines expected from highly ionized plasma are clearly seen.

3.4. Spectral Distribution of Point Sources

In order to study spectral distribution of the point sources, we calculated the spectral hardness ratio (HR) for individual sources. We corrected for positional difference of the instrumental response and difference of the exposure time, such that the corrected count rates are those expected when source are located at the ACIS-I aim point and observed for 100 ksec exposure. We defined the hardness ratio as $HR \equiv (H-S)/(H+S)$, where H is the corrected count rate in the hard energy band ($3-8$ keV), and S is that in the soft energy band ($0.5-2$ keV). In figure 3, we show histogram of the spectral distribution of the point sources (left), and the counting rate vs. HR ratio diagram (right).

From figure 3 (left), we can see that the softest sources with $-1 \leq HR \leq -0.8$ are most numerous. The number of sources decreases as HR increases, but it increases again as

HR exceeds 0.6. If we see the counting rate vs. HR diagram (figure 3, right), relatively dim sources with the corrected count rates $\leq$ 100 cts/100 ksec seem to be clustered into two distinct classes, very soft sources with $HR \leq -0.8$ and very hard sources with $HR \geq 0.6$. Brighter sources with the corrected count rates $\geq$ 100 cts/100 ksec do not seem to have such a tendency.

3.5. Point Source Energy Spectra

Individual sources are too dim to make energy spectra, so we combined sources with similar HR to make a single energy spectrum to study characteristics of the point sources as a spectral class. We combined 91 soft sources with $HR \leq -0.8$ and 44 hard sources with $HR \geq 0.6$, respectively. In Figure 4, we show these energy spectra.

The combined soft spectrum may be roughly fitted with a thin thermal plasma emission model with $kT = 0.76 \pm 0.04$ keV with the interstellar hydrogen column density $N_H = (1.0 \pm 0.1) \times 10^{22}$ cm^{-2}. The small column density relative to the Galactic value ($\sim 6 \times 10^{22}$ cm^{-2}) suggests these are nearby sources, and the low temperature thermal spectra suggests they are X-ray active stars. On the other hand, the hard spectrum may be fitted with a power-law with the index 1.2 ± 0.4, and $N_H = (8.0 \pm 2.4) \times 10^{22}$ cm^{-2}. The large column density and the flat spectrum are consistent with the idea that most of the hard sources are extragalactic AGN. However, the column density is slightly higher than the Galactic value, and the spectral slope is also slightly flatter than that expected from the composition of dim AGN composing cosmic X-ray background (1.4). These facts, as well as the hint of iron K-line emission or edge feature in the composite energy spectrum (figure 4, right), suggests there are several Galactic hard X-ray sources which have flat spectra and iron emission or edge feature. Quiescent dwarf novae are likely candidates for the Galactic hard X-ray sources with such spectral characteristics (Mukai and Shiokawa 1993; Watson 1999).

3.6. Point Source Time Variation

We have studied time variation of the point sources. For each source, we made light curves with 3000 sec and 10000 sec bins. For each light curve, we performed the Kolmogorov-Smirnov test, and the source is considered to be variable if both light curves show the variation above the 99.9 % significance. Thereby, 17 sources are found to be significantly variable. Among them, 13 source have the $HR < 0$ and 4 sources have $HR > 0$. Soft sources with $HR < 0$ tend to show flare-like variations. Typical flares from some of the soft sources are shown in figure 5.

4. Discussion

4.1. Origin of the Diffuse hard X-ray emission

We found that GRXE has a truly diffuse origin, then the question is how to produce and maintain such high energetic plasma. However, there are problems in interpreting GRXE in terms of simple equilibrium thermal plasma. The plasma temperature needed to explain the observed spectra, 5 – 10 keV, is much higher than that can be bound by Galactic gravity (Warwick et al. 1985). Also, energy density of GRXE, $\sim$ 10 eV/cm^3, is one or two orders of magnitude higher than those of other constituents in the interstellar space, such as cosmic rays, Galactic magnetic fields, or ordinary interstellar medium (Koyama et al. 1986; Kaneda et al. 1997). We do not know how to heat the plasma gas up to such a high temperature, and hold the hot gas within the Galactic plane.

On the other hand, strong diffuse gamma-ray ($\sim$ 100 keV – 1 MeV) emission is observed from the Galactic plane (e.g., Gehrels and Tueller 1993; Skibo et al. 1997), which is suggested to have a non-thermal origin, as the energy spectrum is represented with a power-law without a thermal cut-off. GRXE, besides the thermal component, also has a power-law hard tail component which extends above $\sim$ 10 keV (Yamasaki et al. 1997; Valinia and Marshall 1998). This hard-tail component seems to be smoothly connected to the gamma-ray component (Valinia et al. 2000a), although their physical relationship has not been fully understood.

Currently there are no accepted theoretical models which can explain the origin of both GRXE and gamma-ray emission. Some argue that interstellar magnetic field is playing a significant role to heat and confine the hot plasma (Tanuma et al. 1999). Others argue that interaction of low energy cosmic-ray electrons (Valinia et al. 2000b) or heavy ions (Tanaka et al. 2000; Tanaka 2002) with interstellar medium is mainly responsible for GRXE and gamma-ray emission. Different heating or acceleration mechanism of the plasma will result in different plasma conditions, which are reflected in the emission lines. From precise measurements of the iron emission lines, presumably performed with XMM, we may diagnose the plasma and will strongly constrain the origin of GRXE.

4.2. Origin of the Point Sources

We concluded that most of the hard X-ray point sources discovered with Chandra are extragalactic, since the number of hard X-ray point sources does not significantly exceed that expected for extragalactic sources. From statistical arguments, we concluded that number of Galactic hard X-ray point sources between the flux ranges 3×10^{-15} and 2×10^{-13} erg s^{-1} cm^{-2} (2–10 keV) does not exceed $\sim$ 260 sources/degree^2 (90 % upper-limit; Ebisawa et al. 2001), while the number of extragalactic source is $\sim$ 560 sources/degree^2 (e.g., Giacconi et al. 2001). In other words, among the $\sim$ 79 point sources (4 σ confi-

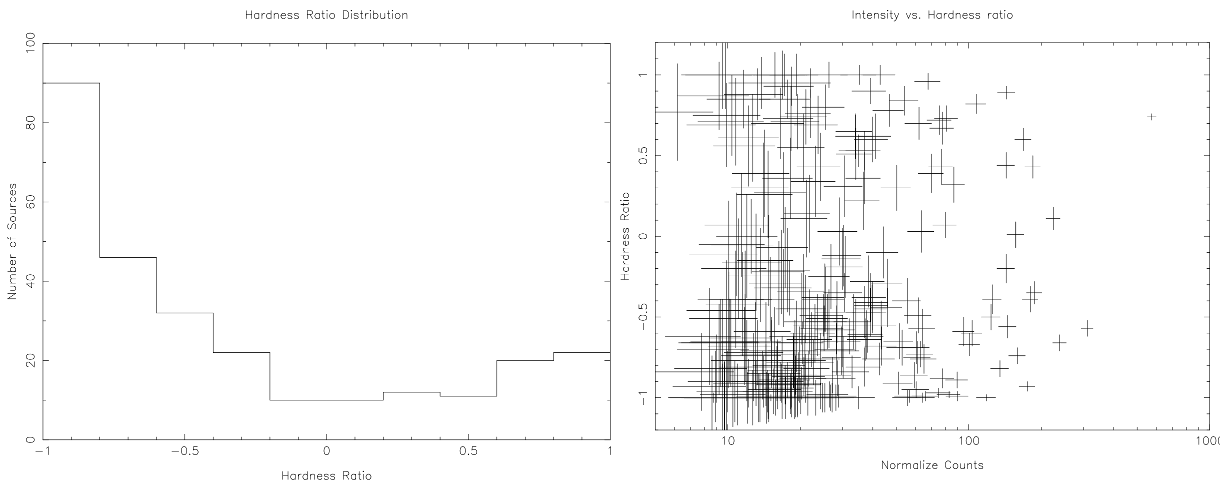

Figure 3. Histogram of the hardness ratio distribution of the sources (left) and the count rate vs. hardness ratio diagram (right).

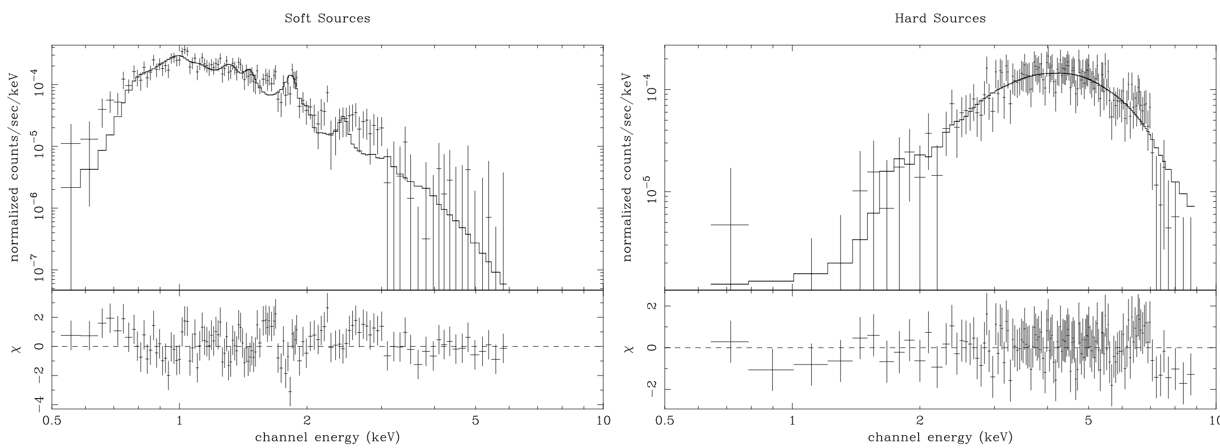

Figure 4. Energy spectra of the combined soft sources (left) and hard sources (right).

dence) we detected in our AO1 and AO2 Chandra fields (250 arcmin^2; Figure 1), there may be up to ~ 18 Galactic sources. From precise X-ray spectral observations, we may tell which sources are Galactic ones such as quiescent dwarf novae (Mukai and Shiokawa 1993; Watson 1999). Also these Galactic sources are likely to be identified by near-infrared observations, while extra galactic sources will be completely obscured and may not be visible in infrared.

Soft point sources are most likely nearby X-ray active stars, as they have small interstellar hydrogen column densities and low plasma temperatures. They are dim in optical lights (only small fraction was identified), and several sources show flare like time variations; these facts suggests the soft sources are mostly late type stars whose X-ray emission is due to their magnetic activities. Nature of these soft sources will be also clarified by more precise X-ray spectral observations and the follow-up near-infrared observations.

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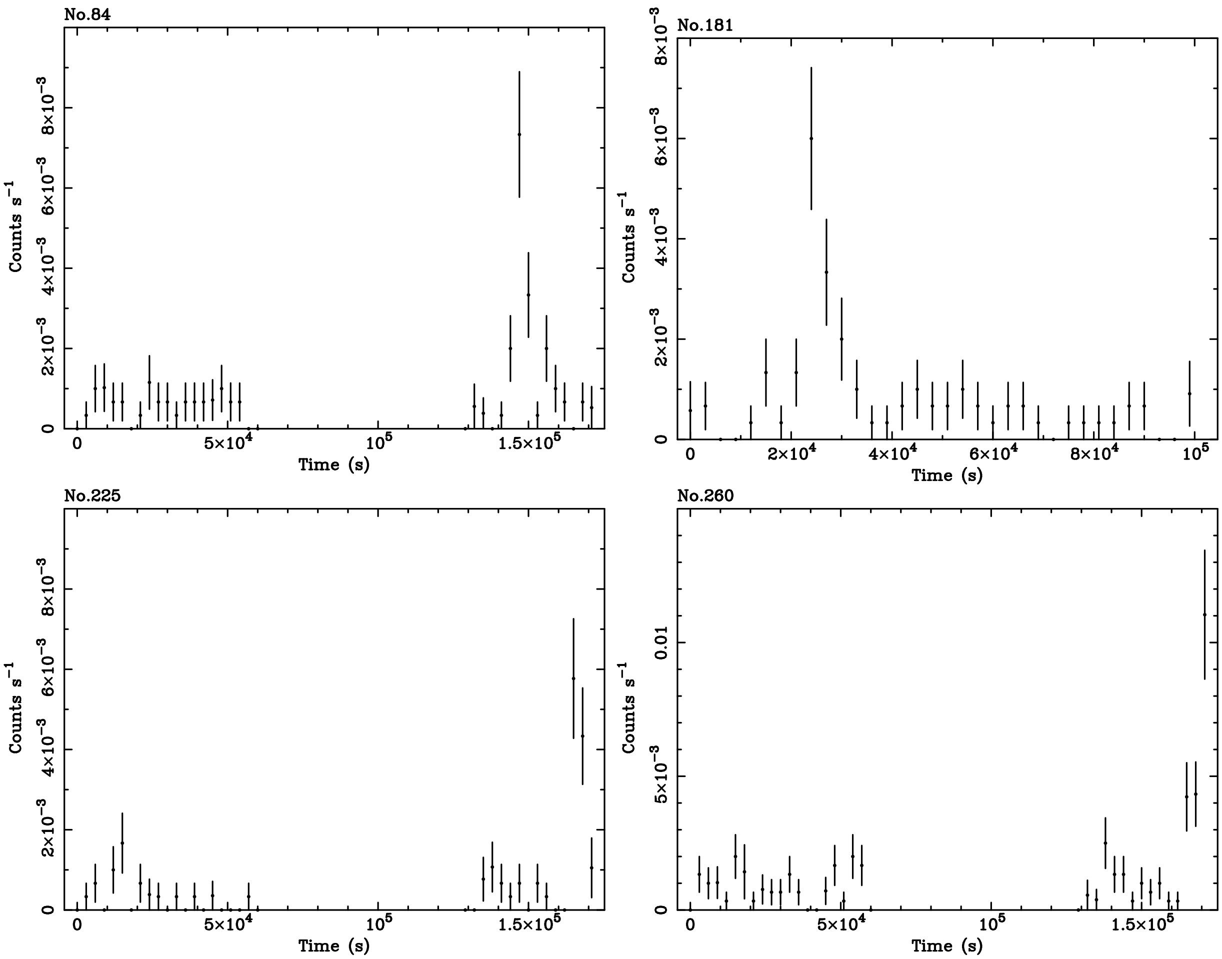

Figure 5. Flare-like light curves of some of the variable sources with soft spectra.

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